NISTIR 6873

Control Strategies for APACTS Micro-Macro-Manipulator - Integration

Richard J. Norcross

U. S. DEPARTMENT OF COMMERCE
Technology Administration
Intelligent Systems Division
National Institute of Standards
and Technology
Gaithersburg, MD 20899

NIST
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce

NISTIR 6873

Control Strategies for APACTS Micro-Macro-Manipulator - Integration

Richard J. Norcross

U. S. DEPARTMENT OF COMMERCE
Technology Administration
Intelligent Systems Division
National Institute of Standards
and Technology
Gaithersburg, MD 20899

May 2002

U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

TECHNOLOGY ADMINISTRATION
Phillip J. Bond, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Arden L. Bement, Jr., Director

Disclaimer

No approval or endorsement of any commercial product by the National Institute of Standards and Technology is intended or implied. Certain commercial equipment, instruments, or materials are identified in this report to facilitate understanding. Such identification does not imply a recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Acknowledgement

This report is partial fulfillment of sub-contract AM 02-9802001 with AmDyne Corporation of Millersville, Maryland.

Abstract

The Carderock Division of the Naval Surface Warfare Center is developing the Automated Paint Application, Containment, and Treatment System (APACTS). APACTS will apply anti-corrosive and anti-fouling paints to ship hulls in an environmentally sound manner. To provide accurate motion over very large surfaces, the APACTS motion system employs a self-propelled base carrying a long reach macro-manipulator, which in turn carries a quick response micro-manipulator to maneuver the paint nozzle and containment device. The manipulators run separate but coordinated trajectories whose combination is the path of the paint nozzle. Based on feedback from sensors and the operator's observations, the controller shifts the path to keep the paint nozzle at the appropriate position relative to the surface being painted. The micro- and macro-manipulator trajectories must adapt to the ship hull and ensure the micro-manipulator does not exceed its operating volume. This report compares strategies for correcting the paint nozzle position. These strategies include; direct modification of the macro-manipulator trajectory, modification of the micro-manipulator trajectory during various portions of its trajectory cycle, and alterations to the micro-manipulator trajectory. The experiments discussed in this report show that the best results occurred when the micro-manipulator trajectory shifts immediately upon error detection during the trajectory upstroke and the macro-manipulator trajectory modifies to keep the micro-manipulator centered. The results further indicate an extended period on the upstroke prior to painting enhances overall system accuracy.

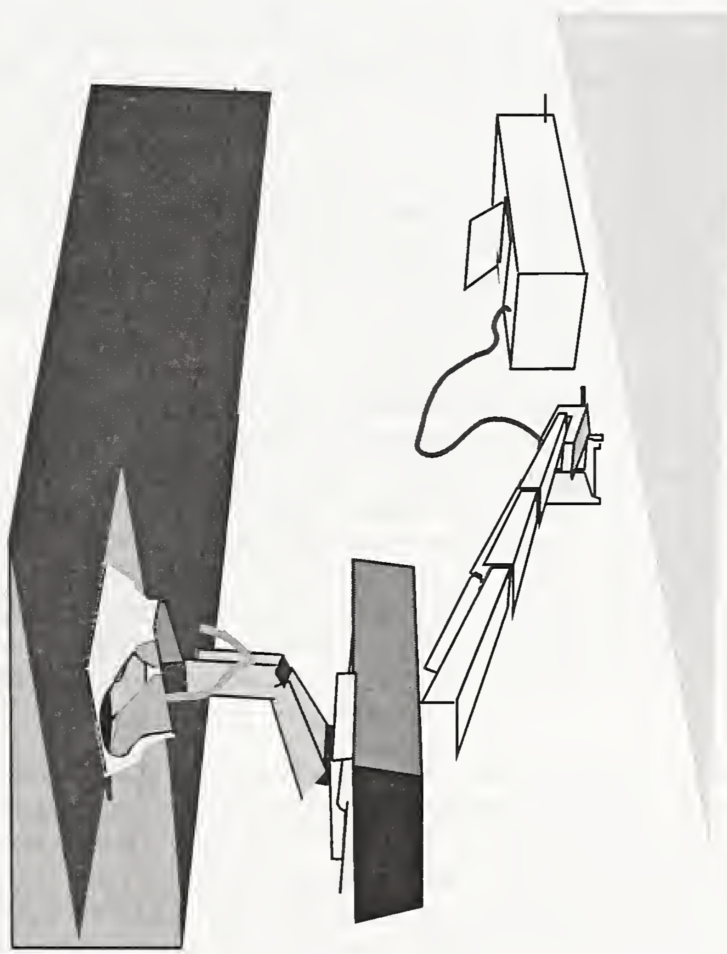
Table of Contents

List of Figures

1 Summary

The Carderock Division of the Naval Surface Warfare Center, Naval Sea Systems Command is developing the Automated Paint Application, Containment, and Treatment System (APACTS) to apply anti-corrosive and anti-fouling paints onto Navy ship hulls in an environmentally sound manner. APACTS (Figure 1) employs three motion components: (1) a self-propelled repositionable base, (2) a long reach macro-manipulator, and (3) a quick response micro-manipulator to move the paint nozzle and containment device along the hull surface. The combined motion trajectories of the macro- and micro-manipulators produce the paint application trajectory. Feedback from sensors mounted on the containment device modify the trajectories in real-time to keep the nozzle at appropriate positions relative to the surface.

Figure 1. APACTS System Concept



The sensors indicate the speed, the position and the orientation of the paint nozzle relative to the surface. The sensors can be fully automatic or can include interpretation by an operator. The controller uses the sensor data to adjust the nozzle path to correctly apply the paint.

While the macro-manipulator trajectory follows the surface at a slow speed, the micro-manipulator moves to keep the nozzle on sequential horizontal stripes. A portion of the micro-manipulator trajectory is equal in magnitude but opposite in direction to the macro trajectory. During these movements, the combined motions hold the nozzle vertically steady over the surface. APACTS applies paint during the steady period then steps down to align for the next stripe.

While the nozzle is steady, the difference between the nozzle position on the micro-manipulator and any mark on the surface reveals the system's vertical position error. The controller can remove the error by shifting the micro trajectory and, when the shifts accumulate, by modifying the macro trajectory. In some instances and in some directions, the controller can correct the error by directly manipulating the macro-manipulator's trajectory. However, experiments indicate that direct macro correction is inferior to micro-manipulator based corrections that remove error by shifting the micro-manipulator trajectory.

Previous experiments tested the system's ability to coordinate macro and micro motions in response to corrective inputs [9]. The experiments verified that the interfaces were sufficient to coordinate and stabilize the two manipulators. However, the system suffered periodic position errors that could cause unacceptable gaps in the paint coverage.

The controller in [9] corrected the position errors only during the paint application portion of the micro-manipulator trajectory. The initial experiments reported here confirmed gaps in the nozzle position. The next experiments attempted to correct the position error throughout the micro trajectory. The controller generated a reference mark to show the proper tool position at all times. The operator observed the position of the surface mark to the reference mark and commanded trajectory shifts to close the observed position errors. The system performance showed no improvement with these modifications. The relative motion was too quick and the manipulator and display components were too slow to permit accurate following.

Subsequent enhancements modified the trajectory definition. Most position errors occurred during the initial portion of the paint stripe. The trajectory was therefore modified to include a period that held the nozzle vertically steady prior to the time for paint application. Thus the controller had the opportunity to correct the position errors prior to paint application and the overall system performance showed significant improvement.

2 Introduction

To guard against the harshness of the sea, ships are covered with anti-corrosive and anti-fouling paints that must be periodically replaced to maintain their effectiveness. During replacement, hazardous airborne particles (HAPs) are inadvertently discharged into the environment diminishing the air quality and endangering shipyard personnel and the surrounding harbor. The Naval Sea Systems Command, Naval Surface Warfare Center, Carderock Division, (NAVSEA NSWCCD), Environmental Quality Department conducts research and development leading to fleet implementation of pollution-control materials, processes, and equipment that enable Navy ships to be environmentally responsible. NSWCCD is responsible for providing the Navy with the technical expertise to solve existing and emerging waste management problems. Pursuant to that responsibility, NSWCCD is developing the Automated Paint Application, Containment, and Treatment System (APACTS) to significantly reduce HAP discharge from the painting operation [1].

The primary components of APACTS are the delivery, containment, treatment, and manipulation systems. The delivery system consists of a paint mixer, strainer, sprayer, nozzle, and associated equipment. The containment system surrounds the paint sprayer and includes a capture shroud, recovery vacuum, hoses, and controls. The treatment system includes waste transport, waste isolation, filter elements, and their support equipment. The manipulation system consists of those devices that move the sprayer and containment shroud. The components complement each other to produce an effective, economic, and environmentally sound system.

The Intelligent Systems Division of the National Institute of Standards and Technology (NIST-ISD) supports APACTS development through the investigation of new and existing technologies to carry, maneuver, and manipulate the APACTS sprayer and containment system. Because a single manipulator would be unable to achieve all of the Navy's performance requirements at an acceptable cost, APACTS uses a series of three manipulators to position the system about the dry dock, to reach along the hull, and to maintain proper standoff and motion. After the mobile base positions APACTS in or around the drydock, a long reach but slow response macro-manipulator carries a high accuracy, fast response micro-manipulator to simultaneously provide sufficient reach and accuracy.

The combination of dissimilar manipulators has several names including macro-micro, macro/micro, maxi-mini, and major-minor. Many researchers have investigated macro-micro control [2] - [8]. These approaches rely primarily on either a well-defined trajectory or a well modeled pair of manipulators. While none of these approaches adequately address the problems of working throughout a very large volume in a poorly defined environment, several micro-macro control strategies may be extended to the APACTS problem.

This report reviews the interaction between the sensors and the manipulator trajectories, and between the micro-manipulator and macro-manipulator trajectories. These experiments indicate superior results occur when: the micro trajectory shifts immediately upon error detection, the micro-manipulator trajectory includes an extended upstroke, and the macro-manipulator trajectory changes to keep the micro-manipulator centered.

3 Methods, Assumptions, and Procedures

APACTS will paint wide vertical swaths on any hull surface by spraying sequential horizontal stripes. The experiments discussed below, tested methods to follow complex surfaces while periodically maintaining the manipulator end point over evenly spaced surface positions. The experiment's trajectories are the vertical component of the APACTS trajectory.

The experiment's trajectory periodically held the manipulator end point over a series of marks on the target surface. APACTS used two manipulators connected in series. The end point was held in place by driving one of the manipulators in an equal but opposite direction of the other. The second manipulator (the micro-manipulator) periodically moved in the same direction as the first (the macro-manipulator) to step the end point to the next surface position. Given the size and mass of the manipulator, the manipulator controller was unable to maintain reasonably accurate positions, and position errors became evident during the hover.

The experiment methodology assumed that the end-point errors were primarily attributable to errors in the macro-manipulator trajectory. Different runs of the experiment compared several error correction methods. One method permitted the operator to directly adjust the macro-manipulator's speed. In the other methods, an operator observed the effect of the error on the tool position through a camera on the micro-manipulator and, via a joystick, offset the micro-manipulator's trajectory as necessary to remove the error. The micro-manipulator communicated the offsets through the micro-macro interface and the macro-manipulator adjusted its trajectory to re-center the micro-manipulator.

Each experiment began with an operator maneuvering the manipulator to a random point at the high end of one of two test surfaces and initiating the combined trajectories. The manipulator trajectories were similar for each experiment and contained no a priori knowledge of the surface. A camera, mounted at the end point of the second manipulator, fed the tool view of the surface to a computer that logged the run. An evaluator replayed the log and recorded the vertical position error at regular intervals during each stripe. The evaluation was based on the percentage of times the end point was within some tolerance within each stripe.

3.1 Manipulators

The experiment used two serially-connected manipulators to carry a collection of sensors along a target surface. A larger, slower manipulator (the macro-manipulator) carried a smaller, faster manipulator (the micro-manipulator) which carried a rod containing the sensors.

The macro-manipulator is a modified ATR-60 aerial work platform (AWP) from Snorkel, Inc. of St. Joseph, MO. The standard AWP has digital proportional valves on several of its actuators. The experiment's AWP has similar digital proportional valves on all actuators and each actuator is fitted with absolute position and relative motion sensors. Servo control modules monitor the actuator motion and adjust the oil flow through the valves to cause the actuator to follow a motion path. A supervisory controller coordinates the actions of the servo modules such that the AWP's basket can follow Cartesian paths or a surface as shown in Figure 2. The macro-manipulator's supervisory controller [10] updates the goal position at 8 Hz. The actuator controllers close the actuator servo loop at 30 Hz.

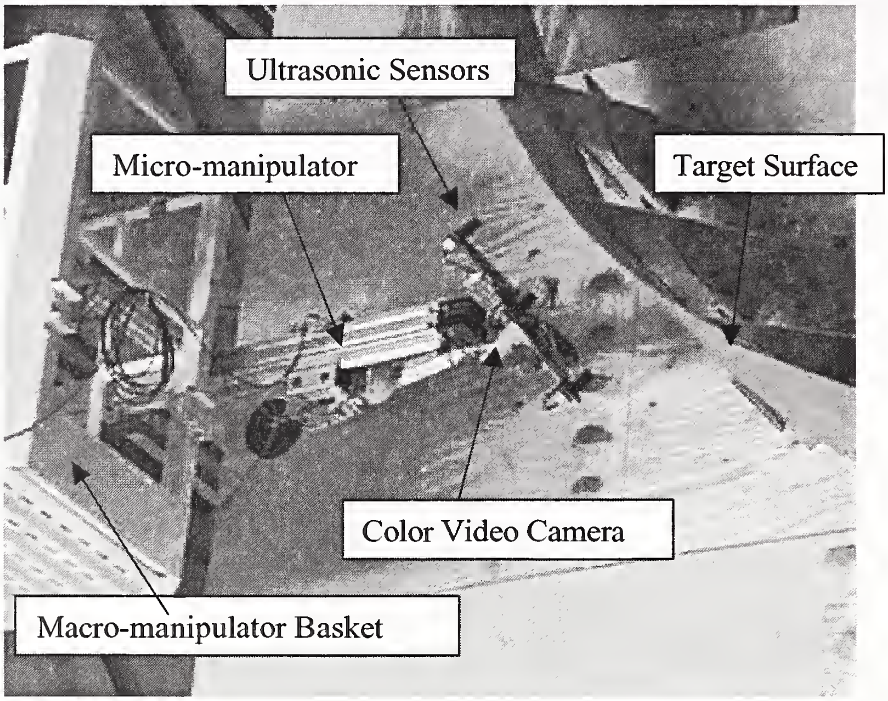
Figure 2. Modified ATR-60 AWP

The experiment's micro-manipulator has three serially-linked actuators that position and orient a 60 cm (2 ft) bar within a vertical plane (Figure 3). The manipulator uses a Dell Inspiron 3800 laptop computer running National Instruments LabView under Windows NT to compute position goals for each of the actuators every 15ms. An Inside Out Edgeport USB Converter delivers the goal points from the laptop to the actuators via a serial line. The actuators are Smart Motors (Anamatics, Inc. of Carlsbad, CA) operating in Anamatics'

“Extended Cam Mode” that smooths discreet point goals at the motor. A micro-controller (Little Star from Z-World, Inc) generates a constant 8533 Hz quadrature encoder signal to drive a virtual input cam. The position goals vary the output cam to produce the desired motion of the three actuators.

The manipulator carries three Migatron RPS-401A ultrasonic sensors to measure the surface distance at three points in front of the manipulator. The micro-controller, that generated the simulated cam from the previous paragraph, reads the sensor outputs and returns their values to the coordinating controller via a serial line and the USB converter. The controller uses the data to compute the distance, orientation, and curvature of the surface.

Figure 3. Micro-Manipulator

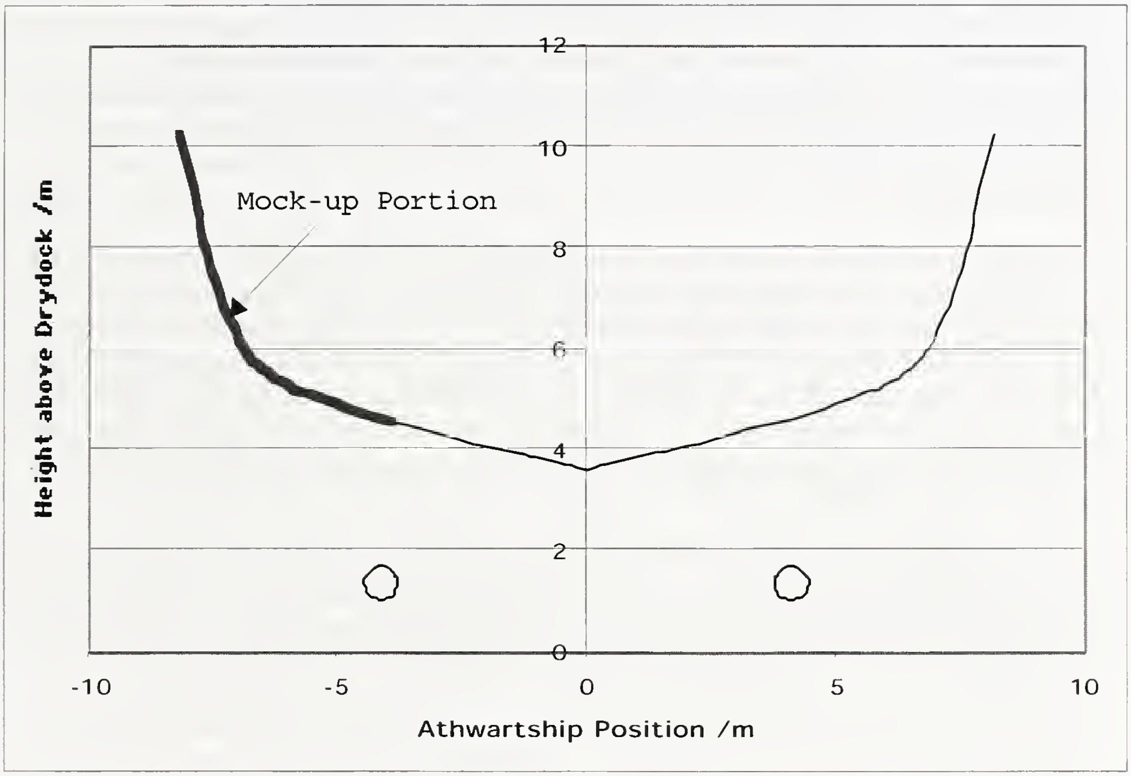


The micro-manipulator carries a small color video camera that provides position feedback to the operator during the experiment. A paper target with regularly spaced sets of colored lines cover the target surface. The position of those lines on the video screen comprises the position feedback. A Macintosh 7600/120 computer running Avid VideoShop records the video images for subsequent evaluation.

3.2 Target Surface

The manipulators followed two surfaces in the experiments. The first was a 12 m (40 ft) high vertical wall. The second was a mock-up of frame 420 of a DDG-51 (Figure 4 and Figure 3). The frame had constantly changing curvature and a minimum radius of curvature of 1.8 m (6 ft) which matched the original APACTS goal [1].

Figure 4. DDG-51 Frame 420 Outline



Targets, with evenly spaced sets of colored horizontal lines at 15 cm (6 in) intervals, covered both test surfaces. The lines provided a visual reference for the operator to monitor and correct the vertical position of the manipulator's tool point (i.e., the camera). During expected APACTS operations, the previous paint line would provide the visual reference to the operator. Thus the surfaces were reasonable representations of hull surfaces that APACTS is expected to encounter.

3.3 Trajectory

The experiment uses the vertical component of the vertical compensation trajectory discussed in [11]. Under the vertical compensation trajectory, APACTS paints in vertical swaths, where a swath is a set of horizontal stripes painted

sequentially from top to bottom. The needs of the paint, the shipyard, and the APACTS machinery determine the trajectory. When requirements permit, extra cycle time can be used to enhance overall performance. The test trajectory represents typical parameters with specific compensation for limits to the available sensors.

In an APACTS application, the desired production rate, the paint spray width, the paint application speed, the stripe width, and the acceleration limits determine the micro-manipulator's trajectory. Independent system and application constraints limit each factor. For example, the micro-manipulator's accelerations generate forces on the macro-manipulator that can excite undesirable oscillations. Thus the macro-manipulator's stiffness limits the micro-manipulator's accelerations. Similarly, the micro-manipulator reach restricts the stripe width. The characteristics of the specific paint batch dictate the paint application speed and the spray width. The shipyard's requirements set the production rate.

Under most scenarios, more time is available for the cycle than required for the vertical motion. The trajectory consumes the extra time: by increasing the production rate, by reducing the acceleration limits, by providing an idle period prior to the upstroke, or by including an extra up stoke prior to painting. Each alternative has specific advantages. Increased production is always desirable. Reduced accelerations improve the macro-manipulator handling. An idle period minimizes the total vertical motion. And, as will be shown below, an extra up stroke period improves system accuracy.

The test trajectory imitates an APACTS application with a 15 cm (6in) effective spray width (aligned vertically), a 72 cm/s (32 in/s) nozzle speed (applied horizontally), and 240 m^2/h (2600 ft^2/h) production rate. The nominal macro-manipulator trajectory moves the basket vertically down a wall at 3 cm/s (1 in/s). The 72 cm/s nozzle speed and the 15 cm spray width are atypical. However, limitations of the available vision sensor require the narrow spray width and the increased nozzle speed compensates so other parameters are representative.

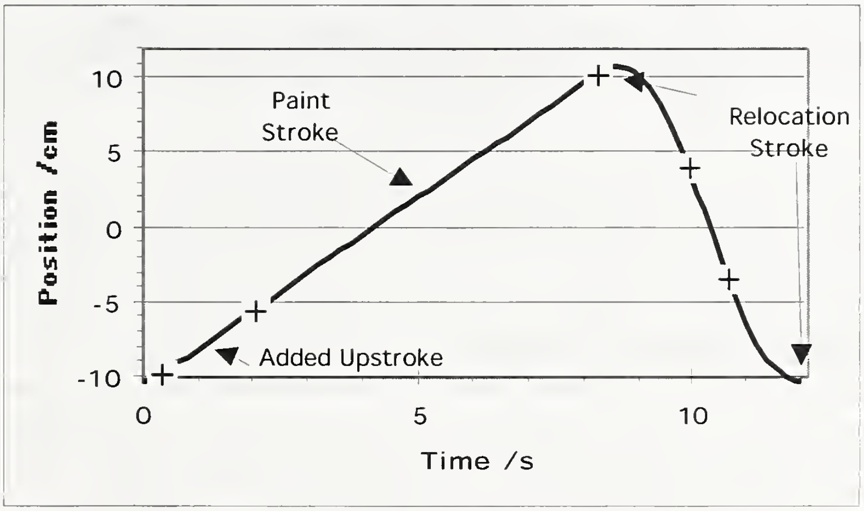
3.3.1 Micro-Manipulator Trajectory

The micro-manipulator's trajectory is a six segment quadratic spline with a continuous first derivative. The paint application portion and the total cycle time of the trajectory is the same for all tests of all of the control strategies. Likewise, none of the trajectories include surface specific information and execute without regard to the surface being followed or the starting point on that surface. During execution, sensors on the manipulator detect the surface's relative position and orientation. The controller and operator monitor the surface position and shift the trajectory to keep the tool point (i.e., the paint nozzle) over the proper position of the surface.

The micro-manipulator trajectory is a repetitive sequence of positions that traverses only a portion of the manipulator's range in any direction. In most of the control strategies, the controller removes nozzle position errors by shifting the micro-manipulator's trajectory into the unused portion of the manipulator's range. For example, if the micro-manipulator can access between 10 and 30 cm in a given direction, and the trajectory requires 10 cm of motion in that direction, then operating between 18 and 28 cm rather than between 15 and 25 cm removes a 3 cm nozzle position error.

Accumulated shifts can exceed the micro-manipulator's operating volume. Therefore the micro-manipulator periodically sends the accumulated shifts (a.k.a., the offset) to the macro-manipulator. The offset triggers a change in the macro-manipulator trajectory that reverses the position errors and re-centers the micro-manipulator.

Figure 5. Sample Micro-manipulator Trajectory

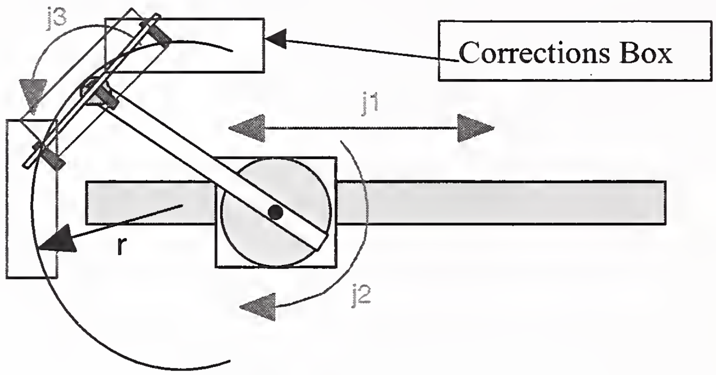


The experiment's micro-manipulator has three degrees-of-freedom. Thus trajectory shifts are available in three directions; towards and away from the surface, up and down along the surface, and rotation about the axis formed by the cross product of these axes. In the experiments, the operator commands the correction along the surface while the controller generates the perpendicular and rotation corrections.

Corrections must keep the manipulator in a position from which other corrections may be made. The corrections along and parallel to the surface form a rectangular box that extends from the manipulator's fundamental trajectory. From within this box, the controller may safely make subsequent corrections. However, extensive rotations within the box brings subsequent motions into the

manipulator's structure. For example, a ninety-degree rotation positions the operating volume over the manipulator's body. Therefore, instead of rotating within the box, the controller rotates the rectangular box around a central point (Figure 6) such that the correction box remains tangential to the surface and clear of the manipulator's structure. The rotation corrections are small and induce offsets in the other directions that are removed by changes to the macro-manipulator trajectory. The distance from the rotation point to center of the corrections box is a significant factor when determining the Macro-Manipulator's trajectory.

Figure 6. Rotation Correction on Micro-manipulator



3.3.2 Macro-Manipulator Trajectory

The macro-manipulator trajectory was the same for all runs of the experiment on both surfaces. The macro-manipulator moved the micro-manipulator down the surface at a slow, and slowly changing, speed. The controller modified the macro-manipulator's direction and speed based on sensor data.

The basic macro trajectory is a constant velocity jog. The macro-manipulator's nominal speed is the quotient of the Production Rate and the Swath width. For these experiments, the trajectory begins at 3 cm/s (1 in/s). The jog direction is a vector parallel to the surface. The controller determines the direction from the sensors on the micro-manipulator. Both the direction and speed vary during the run.

The sensors constantly measured the distance to the surface. From the sensor distances, the sensor spacing, and the micro-manipulator kinematics, the controller computed the slope of the surface and commanded the macro-manipulator along that direction.

The macro-manipulator's commanded speed is a function of the radius of curvature of the surface, the radius of the orientation correction, and the nominal speed.

$$Speed_{macro} = Speed_{nominal} \frac{R + r}{R} \quad (1)$$

Where
r is the distance used in the rotation correction.
R is the surface radius defined by:

$$R = \frac{\overline{\alpha}_i - \overline{\alpha}_{i-1}}{W} \quad (2)$$

$\overline{\alpha}_i$ is the mean surface angle of the i'th stripe.
W is the width of the stripe.

The controller computed the surface radius from the average surface angle during the previous two paint strokes. Although, the surface angle was constant during the paint stroke, the controller measured the angle through a combination of the manipulator's actuator positions and the sensor readings. The combination generated noise in the measured surface angle that caused unacceptable errors in the surface radius calculation. The mean of all of the readings from the paint stroke provided a simple filter for the calculation of the surface radius.

Modification of the macro-manipulator speed requires a similar modification to the micro-manipulator speed. For the nozzle point to remain over a point on the surface, the micro-manipulator must move at the same speed but opposite direction from the macro-manipulator. Therefore, when the surface curvature requires a change of the macro speed, the micro trajectory must be similarly distorted. This distortion may be a change of the micro-manipulator speed or multiple small shifts of the micro-manipulator trajectory. These experiments use the latter approach.

The trajectories for the micro and macro-manipulators are independent but intertwined. Neither trajectory requires a priori information of the surface. Instead, the controller shifts and distorts nominal trajectories in response to the real-time sensor readings of the surface. To keep the nozzle point stationary over the surface, the upward motion of the micro-manipulator must be equal to the downward motion of the macro-manipulator. The controller sets the macro-manipulator's speed as required by the surface and shifts the micro-manipulator's trajectory to generate the proper speed.

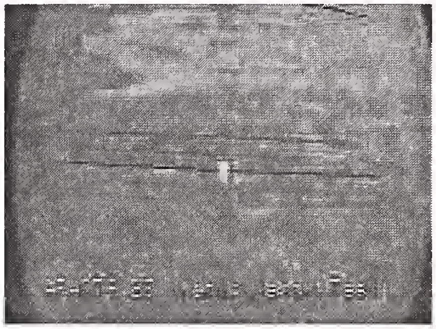
3.4 Operator Interface

The macro-micro control concept relies on observations of the task to determine the motions of the manipulators. The macro-manipulator components do not have the tight tolerances commonly found in servo controlled manipulators. Thus the position based on actuator sensors and the kinematics calculation is unreliable and other sensors must detect the relative pose of the tool point to the

task. While the full APACTS application may use sensors to automatically generate the information, an operator generates the appropriate feedback signals for this experiment.

The experiment's test surface was marked at 15 cm (6 in) intervals with horizontal lines that represented the lower edges of the paint stripes. The micro-manipulator carried a small camera, whose video signal was displayed on a monitor at the control station. Markings, superimposed on the video signal, gave the operator a reference to assess the position of the camera relative to the surface. Figure 7 shows the reference box used during the control strategies that modified the micro-manipulator's position. The monitor displayed additional marks to assist the operator in the control of motions away from the center.

Figure 7. Sample Monitor Screen



In the upper left corner of the operator's monitor, the controller displayed the distance from the sensors to the surface. The controller maintained the standoff during the test runs. The monitor displayed the value as a check of the controller's performance for the operator.

The operator generated corrections via either a joystick connected to the controller or a virtual dial on the controller interface. Through the joystick the operator added up to ±7.5 cm/s (±3in/s) to the velocity of the micro-manipulator tool point. The operator returned the joystick to zero once the desired shift was observed on the monitor. Via the dial, the operator changed the macro-manipulator speed. The dial included buttons to apply small changes to the macro speed. Depending of the test, the operator used either the dial or the joystick.

3.5 Test Procedure

These experiments compared four control techniques for maintaining nozzle position over a large surface. The operator began each test run by maneuvering the manipulator to a target line near the upper end of the test surface and initiating each manipulator's trajectory. As the manipulator followed the surface, the controller collected distance data from the sensors and maintained the tool point's standoff and surface orientation. A camera provided the tool view of the

surface to the operator who corrected the vertical position over the surface. For each control technique the controller provided the operator with indicators that assisted the operator's corrections. A separate computer recorded the tool view for subsequent evaluation.

For tests along the flat surface, the controller introduced an initial speed error to the macro-manipulator. The error was between 30% and 50% of the nominal speed. The operator was aware of neither the magnitude nor the direction of the error. The tests along the hull mock-up did not include an intentional speed error.

The "Micro Correct during Painting" (μCp) control approach allowed the operator to adjust the micro-manipulator position during the micro trajectory's paint stroke. The controller displayed a reference box, and the operator commanded small position corrections to the micro-manipulator. As the target line rose or fell in the reference box, the operator commanded an up or down shift in the micro-manipulator's position. Through these corrections, the operator kept the nozzle over the target line on the surface. Since the nozzle point hovered only during the paint stroke, the controller provided feedback and accepted the corrections only during the paint stroke.

Under the "Macro Correct" (MC) control approach, the operator took direct control of the macro-manipulator speed. The macro-manipulator's response was too slow to allow the nozzle position to be returned to a specific surface target line within a single paint stroke. Therefore, the controller displayed multiple marks on the monitor. The operator attempted to keep the surface mark at the same grid mark from paint stroke to paint stroke. For all other approaches, the controller provided only a single centered reference mark on the monitor and the operator performed the more difficult task of centering the target line. In addition, video distortion caused the grid mark to cover a greater distance at the edges of the monitor than at the center. These distinctions biased the results slightly in favor of the MC control approach.

"Micro Correct during full cycle" (μCf) included a floating reference mark on the tool view and allowed the operator to constantly make position corrections. When the trajectory was in the relocation stroke, the controller computed the location on the monitor the line should be during each control cycle and displayed a moving mark for the operator to follow.

The "Micro Correct with Extended Upstroke" (μCu) approach added a section to the micro trajectory prior to the paint stroke that matched the velocity of the paint stroke. The operator used this portion to remove errors accumulated during the relocation stroke and returned the nozzle position to within the desired tolerance before the paint application.

To score a test, an evaluator replays a video of the operator's monitor that had been recorded during the test run. The evaluator records the vertical position error at regular intervals during each stripe. The score is the percentage of times

the micro-manipulator end point is within ±0.8 cm (0.3 inch) of the surface marking within each stripe. While the necessary accuracy requirement for proper application of marine paints is unknown, the evaluation tolerance exceeds the assumed requirements of the task. The evaluator collects the scores for each stripe and computes the median, quartile, and extreme values to produce a net evaluation for the control approach. The net evaluations provide a qualitative comparison between the control alternatives.

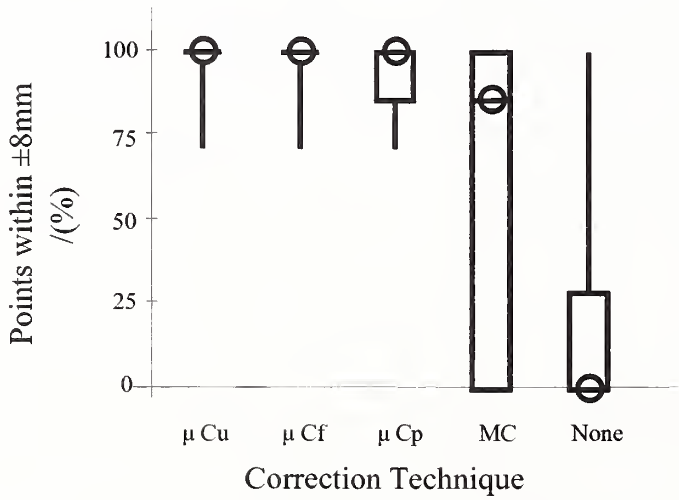
4 Results and Discussions

These experiments compared different control strategies for maintaining the APACTS nozzle on a horizontal stripe. One set of experiments were conducted along a vertical surface, and another set were conducted on a mock-up of a ship hull. The results compared the control technique's ability to handle system and surface induced errors.

This report compares control strategies via box plots. A box plot displays the median value as a circle, the extreme values as vertical lines, and the upper and lower quartile (the middle half of the data) as a box. The box plot provides a rapid, qualitative comparison between alternatives[12].

Figure 8 shows the results of tests along the vertical surface. For these tests, the experimenter adds a small random error to the macro-manipulator speed. This speed generates position errors that the operator removes by modifying the macro-manipulator speed (for the MC approach) or the micro-manipulator position (for other approaches). The results compare the ability of the control techniques to handle system errors.

Figure 8. Results of Runs on Vertical Surface

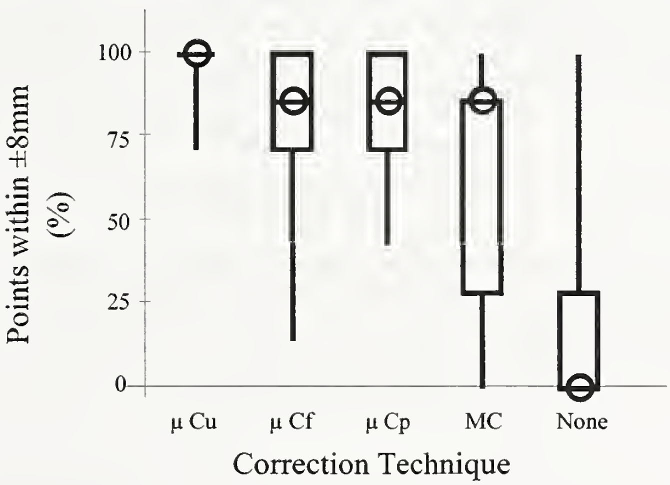


All of the micro-manipulator correction techniques performed well on the vertical surface. Despite a favorable bias in the evaluation criteria, the MC

technique had difficulties removing the initial speed error. The macro-manipulator responded slowly and the operator was required to observe the effect of the correction before making subsequent corrections. When the operator attempted to revise the correction too early the system became unstable, running off one limit, then running off the other. However, once the operator closed on the correct speed, the MC system performed well at maintaining the position and several stripes were completely within the tolerance.

The operator conducted a second set of experiments along the hull mock-up (Figure 9). For these tests, the experimenter did not add an error to the macro-manipulator speed. The test ran from a flat surface, around a 2 m (6 ft) radius curve, and onto another flat surface. The controller adjusted the macro-manipulator speed and direction for the varying surface radii. Various modeling and system inaccuracies generated position errors throughout the run. For example, the controller had no a priori information on the shape of the surface and computed the surface radius (and macro speed) based on the previous, not current, surface. Also, due to the increased inertia, the macro-manipulator's horizontal motion was less accurate then its vertical motion. The operator removed errors by modifying the macro-manipulator speed (for the MC approach) or the micro-manipulator position (for other approaches). The tests compared the ability of the different control techniques to handle surface induced errors.

Figure 9. Results of Runs on Hull Mock-up

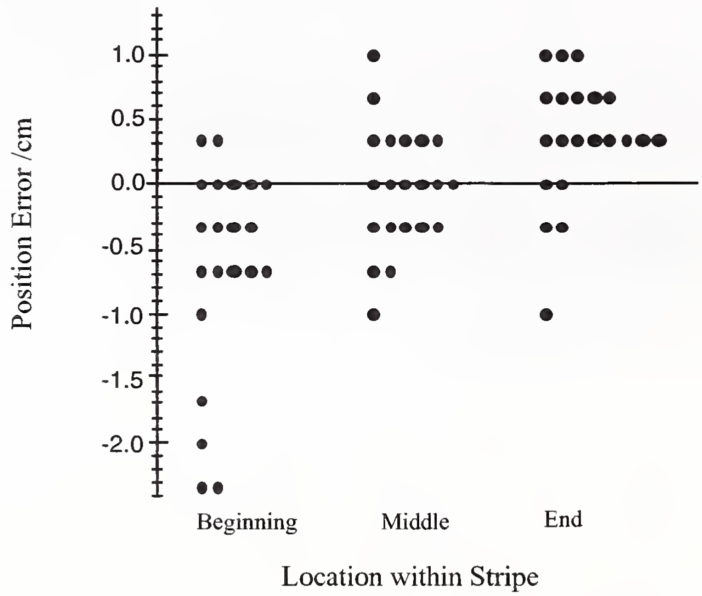


Although the evaluation requirement is less stringent for the Macro Correction technique, this technique was again inadequate. Because there was no initial speed error, there was no large initial position error to overcome. The operator achieved the proper nozzle position during some of almost all of the stripes. However, the speed error varied throughout the run and the operator was

unable to determine the proper speed before the proper speed changed. Thus the nozzle position was incorrect for much of each stripe.

Many of the micro-manipulator correction techniques also had difficulties on the sharply curved surface. To investigate why, the operator conducted a run of the Micro Correction during Paint (µCp) technique while displaying the grid normally used to evaluate the MC technique (Figure 10). The results showed the difficulty derived from the accumulation of errors during the relocation stroke. At the beginning of the paint stroke, the nozzle was often a full centimeter outside of the tolerance. The operator removed the error quickly, but, due to the magnitude of the correction, overshot the desired goal. The result was a number of stripes where the nozzle was temporarily outside of the tolerance.

Figure 10. Dot Plot of Micro Correction during Paint Stroke Run



The operator was unable to improve the system performance by making additional micro position corrections during the relocation stroke. The Micro Correct during Full Stroke (µCf) technique permitted the operator to correct the micro-manipulator position throughout the micro trajectory, However during the relocation stroke, the relative speed between the camera and the surface rose rapidly from 0 cm/s to 12 cm/s (5 in/s). Furthermore, the camera did not maintain perpendicularity to the surface during the relocation stroke and the computed line position was incorrect. Thus the relocation was too quick and computed position too inaccurate for the operator to respond adequately. The results for µCf showed no improvement over correcting during the paint stroke alone.

The Micro Correct with Extended Upstroke (µCu) technique displayed adequate performance on both surfaces. The Extended Upstroke technique had several

disadvantages. The extended upstroke trajectory was taller but had the same duration. Thus the relocation velocities and accelerations were greater then the other techniques. The increased accelerations were expected to cause increased position errors. However, the errors were removed prior to painting in almost all of the stripes.

5 Conclusions

Many techniques are available to coordinate the control of the APACTS nozzle position in a macro-micro system. These techniques are either macro-manipulator based or micro-manipulator based. On flat surfaces, all of the techniques generate sufficient accuracy for APACTS. On irregular surfaces with unidentified disturbances the micro-manipulator based techniques are superior.

The control techniques vary the method to correct the macro-manipulator trajectory. The macro-manipulator techniques change the speed of the macro-manipulator directly. The micro-manipulator techniques shift the micro-manipulator position to maintain the nozzle position and adjust the macro-manipulator speed slowly to keep the micro-manipulator within its operating volume. The micro-manipulator based control techniques generate better accuracy.

On flat or regular surfaces, where there are no system perturbations, all of the control techniques adequately maintain the nozzle in the proper position. However, on irregular surfaces, such as common to ship hulls, or in situations with unidentified and unmodeled perturbations, small velocity errors accumulate into significant position errors. A control strategy that allows an operator or controller to remove position errors immediately prior to paint application while hovering over the surface is able to maintain a more accurate position during the subsequent paint application stroke.

The tolerance used in these experiments may exceed the requirements to apply marine paints to ship hulls. Furthermore, changes to the APACTS manipulators, such as more responsive actuators or stiffer links, may improve the system performance of any of techniques to the tolerance used here. However, a position control strategy that includes a short period immediately prior to the paint application will provide superior end point control regardless of the tolerance desired or the specifics of the structure.

6 Recommendations

There are two recommendations based on the results of these experiments. Primarily, the APACTS control system should provide a period of hover prior to the painting stroke of the micro-manipulator's trajectory and allow micro-manipulator position corrections there. Second, experiments should be conducted to determine the actual position tolerance requirements for APACTS' targeted paint systems.

7 References

[1] Carderock Division, Naval Surface Warfare Center, SOL N00167-97-SS-R1, "Mechanical Ship Hull Paint Application System For Use in Drydock", Commerce Business Daily, April 10, 1997.

[2] T. Yoshikawa, K. Hosoda, T. Doi, H. Murakami, "Dynamic Trajectory Tracking Control of Flexible Manipulator by Macro-Micro-manipulator System", Proc of ICRA, pp. 1804-1809, 1994.

[3] T. Yoshikawa, K. Harada, A. Matsumoto, "Hybrid Position/Force Control of Flexible-Macro/Rigid-Micro-manipulator System", IEEE Transactions on Robotics and Automation, Vol. 12, No. 4, Aug 1996.

[4] O. Khatib, "Reduced Effective Inertia in Macro/Mini Manipulator Systems", Proceedings of ACC, pp. 2140-2147 (1988).

[5] K. Nagai, T. Yoshikawa, "Impedance Control of Redundant Macro-Micro-manipulators", Proc. of Int'l Conf on Intelligent Robots and Systems, pp. 1438-1445, 1994.

[6] A. Sharon, N. Hogan, D. Hawitt, "High Bandwidth Force Regulation and Inertia Reduction Using a Macro/Micro-manipulator System", IEEE ICRA, PP. 126-132, 1988.

[7] K. Nagai, Y. Nakagawa, S. IWASA, K. Ohno, "Development of a Redundant Macro-Micro-manipulator and Contour Tasks Utilizing its Compliant Motion", Proc. of Int'l Conf on Intelligent Robots and Systems, vol. 1, pp. 279-284, 1997.

[8] T. Narikiyo, H. Nakane, T. Akuta, N. Mohri, N. Saito, "Control System Design, for Macro/Micro-manipulator with Application to Electrodischarge Machining", Intelligent Robots and Systems, pp 1454-1460, 1994.

[9] R. Norcross, "One Degree Micro-Macro-manipulator Integration Test", NIST Technical Report 6562, Gaithersburg, MD 2000.

[10] J. Albus, H. McCain, R. Lumia, "NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM)", NIST Technical Report 1235, Gaithersburg, MD 1989.

[11] R. Norcross, "Trajectory Considerations for the Automated Paint Application, Containment, and Treatment System (APACTS)", NIST Technical Report 6326, Gaithersburg, MD 1999.

[12] J. Neter, M Kutner, C Nachtshiem, W. Wasserman, <u>Applied Linear Statistical Models</u>, Richard D. Irwin, Inc., Chicago, IL, 1996.